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MONITORING SUPERGIANT FAST X-RAY TRANSIENTS WITH *SWIFT*. II. RISE TO THE OUTBURST IN IGR J16479−4514

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ABSTRACT

IGR J16479−4514 is a supergiant fast X-ray transient (SFXT), a new class of high-mass X-ray binaries, whose number is rapidly growing thanks to the *INTEGRAL* observations of the Galactic plane. It has been regularly monitored with *Swift* XRT since 2007 November to study the quiescent emission, the outburst properties, and their recurrence. A new bright outburst, reaching fluxes above 10^{-9} erg cm^{-2} s^{-1}, was caught by the *Swift* BAT. *Swift* immediately repointed at the target with the narrow-field instruments so that, for the first time, an outburst from an SFXT where a periodicity in the outburst recurrence is unknown could be observed simultaneously in the 0.2–150 keV energy band. The X-ray emission is highly variable and spans almost 4 orders of magnitude in count rate during the *Swift* XRT observations covering a few days before and after the bright peak. The X-ray spectrum in outburst is hard and highly absorbed. The power-law fit resulted in a photon index of 0.98 ± 0.07, and in an absorbing column density of $\sim 5 \times 10^{22}$ cm^{-2}. These observations demonstrate that in this source (similarly to what was observed during the 2007 outburst from the periodic SFXT IGR J11215−5952), the accretion phase lasts much longer than a few hours.

Subject headings: stars: individual (IGR J16479−4514) — X-rays: individual (IGR J16479−4514)

Online material: color figures

1. INTRODUCTION

Supergiant fast X-ray transients (SFXT) are a new class of high-mass X-ray binaries associated with blue supergiant companions, several members of which were discovered thanks to the *INTEGRAL* observations of the Galactic plane (Sguera et al. 2005). They are sources with transient X-ray emission concentrated in short and bright flares (with a typical duration of a few hours), a peak luminosity in the range of 10^{36}–10^{37} erg s^{-1}, and a quiescent level of 10^{32} erg s^{-1} (e.g., in 't Zand 2005). The short duration flaring activity is part of a longer accretion phase at a lower level (Romano et al. 2007).

IGR J16479−4514 is a hard X-ray transient discovered by *INTEGRAL* in 2003 August (Molkov et al. 2003). Hard X-ray activity was observed on August 8 and 9, at a level of ~12 mcrab (18–25 keV), while the following day the flux increased by a factor of ~2. Other outbursts caught with *INTEGRAL* in 2003 and 2004–2005 were reported by Sguera et al. (2005, 2006) respectively, with peak fluxes above 10^{-9} erg cm^{-2} s^{-1} (20–60 keV). The recurrent and short outbursts observed from this source led to a suggestion that it belongs to the SFXT class.

A frequent hard X-ray ($E > 20$ keV) flaring activity was recently discussed by Walter & Zurita Heras (2007) who report on 27 short (duration <15 ks) flares and on 11 long (>15 ks) flares in archival *INTEGRAL* data, spanning times from 2003 January 11 to 2005 December 2, with variable fluxes.

IGR J16479−4514 was observed once with *XMM-Newton* (Walter et al. 2006) in 2004 March, when it displayed a low-level X-ray emission. The joint EPIC pn and ISGRI-*INTEGRAL* spectrum was successfully fit with an absorbed Comptonized spectrum, with an intrinsic column density of $(7.7 \pm 1.7) \times 10^{22}$ cm^{-2}, an electron temperature $kT_e > 13$ keV, and optical depth $\tau < 1.8$. The unabsorbed 2–100 keV flux was 1.8×10^{-10} erg cm^{-2} s^{-1}. An upper limit to the presence of an iron line could be placed at EW < 280 eV.

This source is normally detected in the *Swift* BAT transient monitor[7] (15–50 keV) at a level of 4 mcrab and showed 23 flares above 300 mcrab and 4.5 σ significance during the *Swift* mission up to 2008 March, including the ones that triggered the *Swift* BAT on 2005 August 30 (Kennea et al. 2005), 2006 May 20 (Markwardt & Krimm 2006), 2006 June 24, and 2007 July 29.

As reported in Romano et al. (2007) the *Swift* monitoring of the outburst of the periodic SFXT IGR J11215−5952 in 2007 February represents the deepest and most complete set of X-ray observations of an SFXT in outburst. We showed that the accretion phase during the bright outburst lasts longer than previously thought: days instead of hours, with only the brightest phase lasting less than 1 day. Stimulated by these *Swift* results, we are performing the first sensitive X-ray monitoring campaign of the activity of four SFXTs, IGR J16479−4514, IGR J17391−3021, IGR J17544−2619, and IGR J18410−0535, with the main aim of characterizing their activity on long timescales, both the quiescent state and the outbursts recurrence, and to test our model for the outburst mechanism (Sidoli et al. 2007), which involves the presence of a denser and slower equatorial wind component from the supergiant companion star. The results of the first 4 months of the ongoing campaign with *Swift* can be found in a companion paper (Sidoli et al. 2008, hereafter Paper I; see their Fig. 1), where X-ray activity outside outbursts in IGR J16479−4514 is discussed. Here we report on the detailed data analysis of the 2008 March 19 outburst caught by *Swift* BAT (Barthelmy et al. 2008) and followed at softer energies with *Swift* XRT (Romano et al. 2008).

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[7] See data at http://swift.gsfc.nasa.gov/docs/swift/results/transients/weak/IGRJ16479-4514/.

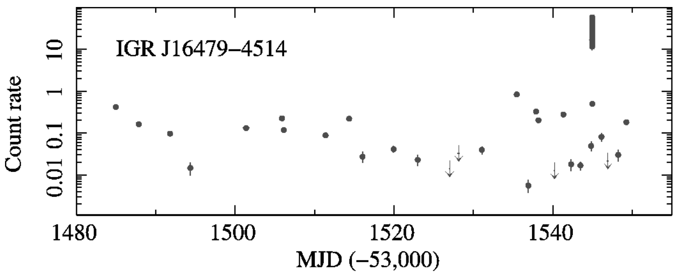

FIG. 1.—*Swift* XRT (0.2–10 keV) light curve of IGR J16479−4514 in 2008, background-subtracted and corrected for pileup, PSF losses, and vignetting. Data before 54,525 MJD are reported in Paper I. The downward-pointing arrows are 3 σ upper limits. [*See the electronic edition of the Journal for a color version of this figure.*]

2. OBSERVATIONS AND DATA ANALYSIS

Swift BAT triggered twice on IGR J16479−4514 on 2008 March 19, first at 22:44:47 UT (trigger 306829; Barthelmy et al. 2008) while *Swift* had been observing it as part of our monitoring program, and then at 22:59:59 UT (trigger 306830). The spacecraft immediately slewed to the target, so that the narrow-field instruments started observing it ~113 s after the first trigger (the slew caused a ~50 s gap in the XRT data, and the XRT points up to ~60 s after the first BAT trigger were collected as one of our pointed observations).

The BAT data were analyzed using the standard BAT software within FTOOLS (`Heasoft`, ver. 6.4). Mask-tagged BAT light curves were created in the standard four energy bands (Fig. 2) and rebinned to achieve a signal-to-noise ratio of 5. BAT mask-weighted spectra were extracted over three time intervals strictly simultaneous with XRT data (§ 3, Fig. 3) from the three continuous streams of BAT data in Figure 2. Response matrices were generated with `batdrmgen`.

The XRT data were processed with standard procedures (`xrtpipeline`, ver. 0.11.6), filtering, and screening criteria by using FTOOLS. We considered both WT and PC data, and selected event grades 0–2 and 0–12, respectively. To account for the background, we also extracted events within source-free regions. Ancillary response files were generated with `xrtmkarf`, and they account for different extraction regions, vignetting, and PSF corrections. We used the latest spectral redistribution matrices (ver. 010) in CALDB. All quoted uncertainties are given at 90% confidence level for one interesting parameter unless otherwise stated.

3. RESULTS

3.1. *Light Curves*

Figure 1 shows the *Swift* XRT 0.2–10 keV light curve of IGR J16479−4514 throughout our 2008 monitoring program, background-subtracted and corrected for pileup, PSF losses, and vignetting. All data in one segment were generally grouped in one point (with the exception of the March 19 outburst, which shows up as a vertical line on the adopted scale). The monitoring program started on 2007 October 26 with approximately two observations per week, but when the source showed signs of increased activity on March 10, the observations became almost daily.

Figure 2 shows the detailed light curves during the brightest part of the March 19 outburst in several energy bands. Figure 3 shows the 4–10/0.3–4 keV and 50–100/15–50 keV hardness ratios. Fitting the 4–10/0.3–4 keV hardness ratio as a function of time to a constant model yields a value of 1.38 ± 0.03 and

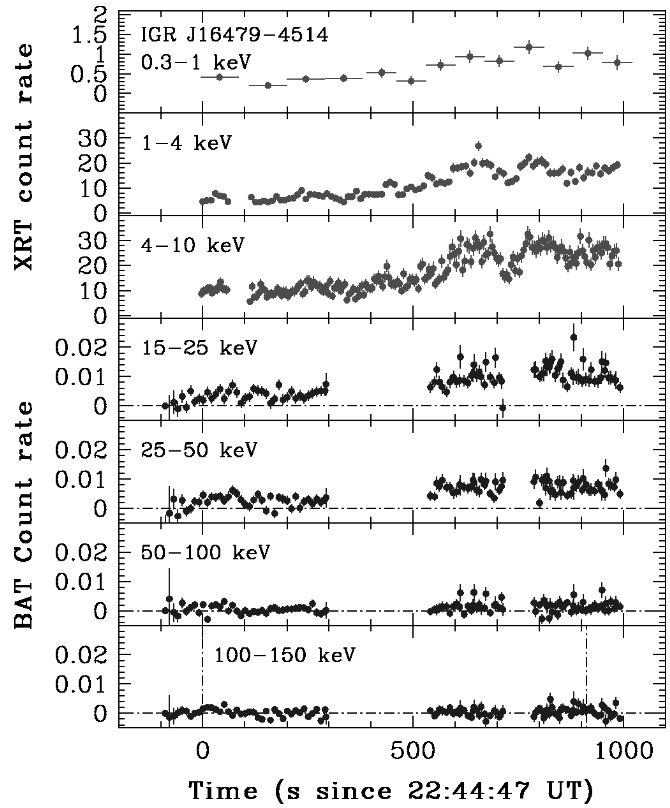

FIG. 2.—XRT and BAT light curves of the 2008 March 19 outburst in units of counts s^{-1} and counts s^{-1} detector^{-1}, respectively. The XRT points up to ~60 s after the first BAT trigger were collected as a pointed observation part of our monitoring program. The gaps in the BAT data are caused by BAT event mode time intervals being limited to less than 600 s to reduce telemetry. The vertical dot-dashed lines in the bottom panel mark the two BAT triggers. [*See the electronic edition of the Journal for a color version of this figure.*]

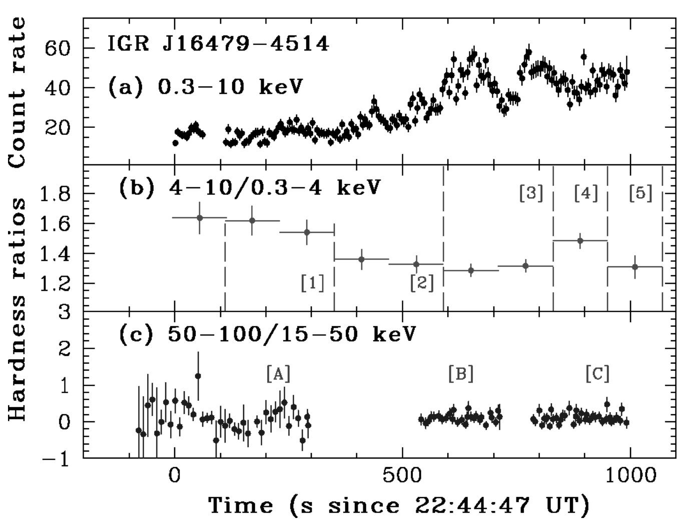

FIG. 3.—X-ray WT mode and BAT event mode hardness ratios during the 2008 March 19 outburst. (*a*) XRT 0.3–10 keV light curve. (*b*) Ratio of the 0.3–4 to the 4–10 keV XRT light curves. The vertical dashed lines mark the five intervals for XRT time-resolved spectroscopy (Table 1). (*c*) Ratio of the 50–100 to the 15–50 keV BAT light curves. [A], [B], and [C] mark the three intervals for joint XRT+BAT spectroscopy (Table 2). [*See the electronic edition of the Journal for a color version of this figure.*]

TABLE 1
Spectral Fits of XRT Data

Spectrum	Mid Time (MJD)	$N_{\rm H}$ (10^{22} cm^{-2})	Γ	χ^2_ν (dof)
Total WT	54544.9551	$5.51^{+0.29}_{-0.28}$	$0.98^{+0.07}_{-0.07}$	0.939 (563)
Part 1	54544.9511	$6.05^{+1.19}_{-1.00}$	$0.83^{+0.26}_{-0.24}$	0.947 (95)
Part 2	54544.9522	$4.92^{+0.70}_{-0.62}$	$0.77^{+0.17}_{-0.16}$	0.997 (149)
Part 3	54544.9555	$5.07^{+0.45}_{-0.41}$	$1.02^{+0.12}_{-0.12}$	0.982 (249)
Part 4	54544.9569	$5.50^{+0.69}_{-0.62}$	$0.93^{+0.17}_{-0.16}$	0.820 (157)
Part 5	54544.9596	$5.91^{+0.82}_{-0.71}$	$1.12^{+0.19}_{-0.18}$	0.796 (128)
Total PC	54544.9986	$5.76^{+2.05}_{-1.71}$	$2.57^{+0.75}_{-0.68}$	471.0[a] (68.93[a])

[a] Cash statistics and percentage of Monte Carlo realizations with statistic < *C*-stat.

$\chi^2_\nu = 3.46$ for 8 degrees of freedom (dof). A general trend is observed for a spectral softening as the flux increases in the XRT bands.

During the 2008 March 19 outburst the peak count rate exceeded the one recorded on 2005 August 30 (Kennea et al. 2005; Paper I) by a factor of ∼5. The total (0.3–10 keV) XRT light curve (Fig. 3*a*) shows an increase in count rate by a factor of ∼5 in ∼13 minutes, and an increase by a factor of ∼350 in ∼3 hr (compared with the first earliest point, not shown in Fig. 3). A corresponding increase is observed in the BAT flux on timescales of minutes.

A timing analysis was performed on WT data ($\Delta T = 884$ s), after having converted the event arrival times to the solar system barycentric frame. We searched for coherent periodicity, but found no evidence in the range 10 ms–100 s.

3.2. *Spectra*

We extracted the mean spectrum of the brightest X-ray emission (obs. 00306829000) and performed a fit in the 0.3–10 keV band of the WT data, which were rebinned with a minimum of 20 counts bin^{-1} to allow χ^2 fitting. An absorbed power-law model yielded an absorbing column of $N_{\rm H} = (5.51^{+0.29}_{-0.28}) \times 10^{22}$ cm^{-2}, a photon index $\Gamma = 0.98 \pm 0.07$, and $\chi^2_\nu = 0.939$ (563 dof; see Table 1). The unabsorbed flux in the 2–10 keV band is 5.8×10^{-9} erg cm^{-2} s^{-1}. A high-energy-cutoff power-law model (`cutoffpl` in XSPEC) yielded $N_{\rm H} = (4.65^{+0.55}_{-0.53}) \times 10^{22}$ cm^{-2}, $\Gamma = 0.16 \pm 0.48$, $E_c = 7^{+10}_{-3}$, $\chi^2_\nu = 0.927$ (562 dof). The *F*-test probability with respect to the absorbed power-law model is 3.154×10^{-3} (2.95 σ); hence, since the cutoff energy is not well constrained, we favor the absorbed power-law model for the XRT data alone. We note however that a cutoff power-law yields a good fit to the joint XRT+BAT data. We also note that the derived $N_{\rm H}$ is in excess of the one along the line of sight, 1.87×10^{22} cm^{-2}.

The X-ray spectrum of the fainter emission (PC data, unabsorbed 2–10 keV flux of 8.95×10^{-11} erg cm^{-2} s^{-1}) is significantly softer: fitted using Cash statistics and adopting an absorbed power-law model model, we obtain $\Gamma = 2.57^{+0.75}_{-0.68}$ and $N_{\rm H} = (5.76^{+2.05}_{-1.71}) \times 10^{22}$ cm^{-2} (*C*-stat = 471.0 for 68.93% of 10^4 Monte Carlo realizations with statistics < *C*-stat).

Upon examination of the best XRT hardness ratio (Fig. 3*b*), we accumulated spectra in five time bins which maximized the variations in hardness ratio and yielded ∼2600–7500 counts per spectrum. Table 1 reports our results.

We extracted three XRT spectra simultaneous with the three BAT spectra in the time intervals 120–303 s, 541–723 s, and 793–1092 s since the BAT trigger ([A], [B], and [C] in Fig. 3), and performed joint fits in the 0.3–10 keV and 14–150 keV energy bands for XRT and BAT, respectively, and applied an energy-dependent systematic error vector to the BAT data. Factors were included in the fitting to allow for normalization uncertainties between the two instruments, which were constrained to be within their usual ranges (0.9–1.1). Several models typically used to describe the X-ray emission from accreting pulsars in HMXBs were adopted. The results are reported in Table 2 and Figure 4. We note that the fit to the BAT data alone obviously results in a steep power law with $\Gamma \sim 3$.

All models allow a good deconvolution of the 0.5–100 keV emission, resulting in a rather flat continuum below 10 keV together with a high-energy exponential cutoff (model `highecut` in XSPEC) at ∼8–20 keV (depending on the time interval). In the Comptonization model (`compTT` in XSPEC; Titarchuk 1994), we adopted a spherical geometry for the Comptonizing plasma, since both geometries allow an equally good deconvolution.

TABLE 2
Spectral Fits of Simultaneous XRT and BAT Data

	Parameters				
HPL[a]	$N_{\rm H}$	Γ	E_c (keV)	E_f (keV)	χ^2_ν (dof)
Part A	$5.6^{+1.2}_{-0.96}$	$0.74^{+0.29}_{-0.29}$	$7.2^{+2.2}_{-1.5}$	$9.9^{+2.9}_{-1.6}$	0.823 (150)
Part B	$5.7^{+0.4}_{-0.6}$	$1.24^{+0.11}_{-0.17}$	6.9 ± 1.0	$17.7^{+2.8}_{-3.2}$	0.982 (264)
Part C	$6.2^{+0.6}_{-0.5}$	$1.15^{+0.15}_{-0.13}$	$6.6^{+1.0}_{-0.7}$	$15.3^{+2.7}_{-1.8}$	1.046 (301)
	$L_{0.5-10}$[c]	$L_{0.5-100}$[c]			
Part A	0.94	2.05	…	…	…
Part B	2.66	5.46	…	…	…
Part C	2.82	5.73	…	…	…
CPL[a]	$N_{\rm H}$	Γ	E_c (keV)		χ^2_ν (dof)
Part A	$5.4^{+1.2}_{-1.1}$	0.17 ± 0.40	$7.4^{+2.3}_{-1.5}$	…	0.845 (151)
Part B	$5.8^{+0.6}_{-0.5}$	1.0 ± 0.2	$15.3^{+3.5}_{-2.6}$	…	1.042 (265)
Part C	6.5 ± 0.6	0.97 ± 0.17	$13.5^{+2.5}_{-1.9}$	…	1.108 (302)
CTT[b]	$N_{\rm H}$	T_0 (keV)	T_e (keV)	τ	χ^2_ν (dof)
Part A	$3.2^{+1.0}_{-0.7}$	$1.57^{+0.24}_{-0.30}$	$7.1^{+3.3}_{-2.0}$	$7.8^{+4.2}_{-3.8}$	0.829 (150)
Part B	2.8 ± 0.4	1.36 ± 0.11	$12.0^{+4.0}_{-2.2}$	$5.3^{+1.0}_{-1.4}$	0.962 (264)
Part C	3.2 ± 0.4	$1.41^{+0.12}_{-0.10}$	$10.8^{+6.4}_{-1.5}$	$5.5^{+0.3}_{-2.2}$	1.00 (301)

Note.—HPL = `highecutpl`, CPL = `cutoffpl`, CTT = `compTT`.
[a] $N_{\rm H}$ is the neutral hydrogen column density ($\times 10^{22}$ cm^{-2}), Γ the power-law photon index, E_c the cutoff energy (keV), and E_f the exponential folding energy (keV).
[b] T_0 is the temperature of the Comptonized seed photons, T_e and τ the temperature and the optical depth of the Comptonizing electron plasma (spherical geometry).
[c] In units of 10^{37} erg s^{-1} derived assuming a distance of 4.9 kpc.

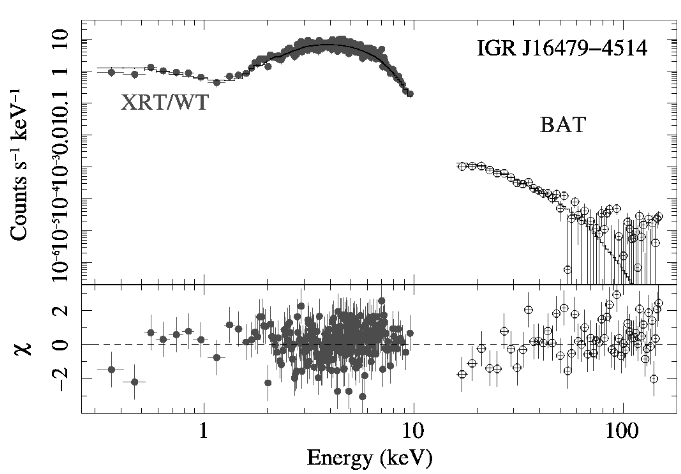

Fig. 4.—Spectroscopy of the 2008 March 19 outburst. *Top*: Data from the second BAT observation (part [C] in Fig. 3) and simultaneous XRT/WT data fit with an absorbed power-law with a high-energy cutoff. *Bottom*: The residuals of the fit (in units of standard deviations). [*See the electronic edition of the Journal for a color version of this figure.*]

4. DISCUSSION

We report on the first simultaneous broadband X-ray spectrum of IGR J16479−4514 in the 0.3–100 keV energy range. The source emission is well fit with the spectral models usually applied to the accreting X-ray pulsars: power laws with a high-energy cutoff (White et al. 1983) and Comptonization models (Titarchuk 1994). The resulting parameters are also very similar to those of this kind of X-ray binary sources.

The time-resolved spectroscopy of the joint XRT-BAT spectrum during the bright flare reveals that the initial part of the flare (part [A]) shows the flattest continuum below 10 keV, together with the lowest high-energy cutoff, with respect to the subsequent brighter part of the emission (see Table 2, parts B and C), in all the three models adopted. No evidence is found for variability in the absorbing column density during the evolution of the bright flare, and also in comparison with the out-of-outburst emission (Paper I). From optical/IR observations of the supergiant companion, Rahoui et al. (2008) derived an extinction $A_V = 18.5$ mag, which translates into an absorbing column density of 3.3×10^{22} cm^{-2} (Predehl & Schmitt 1995) which is in excess of the total Galactic in the source direction (see § 3). Thus there is evidence for neutral absorbing matter local to the binary system. Among the different models used to fit the broadband spectrum, the Comptonization model yielded an $N_{\rm H}$ compatible with the optical extinction, and thus there is no strong evidence that an excess of absorption is local to the X-ray source (and that could be linked to the accreting clumps, if the supergiant wind is inhomogeneous). This could imply that the bulk of the neutral absorbing matter is circumbinary matter, instead of being associated with the accreting clumps (whose matter is very likely totally ionized when approaching the X-ray source). Although the statistics allow a constant value of $N_{\rm H}$ (Table 2), a trend is found in the hardness ratio (Fig. 3*b*), which is decreasing with increasing flux, during the outburst. This is probably the indication of a reduced neutral gas column density, as the circumstellar gas is progressively ionized by the X-ray flare.

Before these observations, IGR J11215−5952 was the only SFXT observed in depth during an outburst (Romano et al. 2007; Sidoli et al. 2007). In that case, the occurrence of the outburst was predictable thanks to the periodic recurrence (Sidoli et al. 2006). For IGR J16479−4514 the outburst could only be caught thanks to our *Swift* monitoring campaign (Paper I).

The source light curve before 54,525 MJD (Fig. 1) has already been reported and discussed in Paper I. It shows a smoothly variable flux, with a dynamic range of more than 1 order of magnitude, which apparently is sinusoidally modulated with a period of ∼24 days (although we caution that only about 2 periods of this suggested periodicity have been covered). During the most frequent monitoring (between 54,535 and 54,544 MJD) preceding the outburst, a highly variable source intensity was observed, with rates going up and down on short timescales of 1–2 days and spanning 2 orders of magnitude at maximum, before reaching the brightest peak. In the total light curve monitored with *Swift*, IGR J16479−4514 spanned almost 4 orders of magnitude in flux in a few days. Moreover, the flux is highly variable on different timescales, from seconds to minutes, days and weeks, revealing a very intense flaring activity, both during the outburst and outside it (Paper I).

The rise time to the peak (at an average rate of ∼17 counts s^{-1} on 54,544.95 MJD) is at most ∼3 hr. After the peak (also monitored by the BAT), the nearest XRT observation (∼1.175 days later) found the source at a much fainter rate (0.085 ± 0.017 counts s^{-1}). This implies that the brightest phase of the outburst lasts 1 day at most, which is a behavior similar to that observed in IGR J11215−5952 (Romano et al. 2007), where the bright emission lasted less than 1 day and then was followed by a much weaker emission, although highly variable, with several shorter (but fainter) flares. This is also consistent with the duration of previous outbursts detected by the BAT.

Rahoui et al. (2008) classify the optical companion as an O8.5 I star located at ∼4.9 kpc. This, together with the highly variable X-ray flux, confirms the classification as an SFXT. In these sources, a subclass of HMXBs, the accretion onto the compact object is very likely through the strong wind from the supergiant donor. The orbital parameters of IGR J16479−4514 as well as the nature of the compact object are still unknown, although the X-ray spectral properties are similar to those of accreting pulsars. Thus, the compact object is probably a neutron star, as in IGR J11215−5952, which hosts a pulsar with a period of ∼187 s (Swank et al. 2007).

Assuming the compact object is a neutron star and the typical parameters for an O-type supergiant (a mass $M \sim 50$–$60\ M_{\odot}$, a radius $R = 25$–$30\ R_{\odot}$, a beta law for the supergiant wind with an exponent $\beta = 1$, a wind terminal velocity of 1800–2200 km s^{-1}, and a wind mass loss of $2.5 \times 10^{-6}\ M_{\odot}$ yr^{-1}; Wilson & Dopita 1985), we can compare the expected X-ray luminosity for Bondi-Hoyle accretion with the observed X-ray emission. The fast (<3 hr) rise to the brightest emission during outburst is difficult to explain with an enhanced accretion rate when the compact object approaches the O-type supergiant companion along its orbit, if we assume a symmetric and homogeneous wind. The same behavior was observed in the periodic IGR J11215−5952 (Sidoli et al. 2007). In this framework, the fainter X-ray emission (10^{34}–10^{35} erg^{-1}) preceding the bright outburst cannot be explained with an orbit with a period shorter than ∼15 days, and an eccentricity lower than ∼0.5. A more detailed light curve modeling cannot be performed at this time, since the orbital parameters are currently unknown.

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Facilities: Swift

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